Comparative Analysis of ANN and PID Controller of Aero-pendulum on Simscape

Aftab Ahmad
aftabahmad@zhcet.ac.in
Department of Electrical Engineering, A.M.U.

Nidal Rafiuddin
nidal.rafi@gmail.com
Department of Electrical Engineering, A.M.U.

Yusuf Uzzaman khan
yusufzkhan@zhcet.ac.in
Department of Electrical Engineering, A.M.U.

***Abstract*: This paper presents the analysis and control of driven pendulum or aero-pendulum simulated on simscape, a classic example of a mechatronic system by using both, conventional Proportional Integral Derivative (PID) and Artificial Neural Network (ANN) Controller. Aero-pendulum has highly non-linear dynamics, therefore its angular position control by using conventional control techniques is very difficult, and the PID controller parameters can only be tuned for single operating point. The work carried out mainly focuses on developing an ANN controller which can overcome the shortcomings of conventional PID controller. An ANN controller has been trained by data acquired from the system when PID controller was incorporated for different operating points. Finally, the angular position control of driven pendulum has been achieved using the ANN controller, having comparable performance and stability with the PID controller. Also instead of using a linearized mathematical model of aero-pendulum for simulation, a 3D multibody model has been developed using simscape, which incorporated all the nonlinearity related to the physical system.**

***Index Terms*— Artificial neural network (ANN) controller, Aero-pendulum, Proportional Integral Derivative (PID) controller, Simscape.**

I. INTRODUCTION

A Simple pendulum system is a mechanical system with periodic motion. It consists of a bob suspended by a light longitudinal string/rod fixed at the tip. The rotation of the vertical plane is governed by a gravitational force [1]. Control of the pendulum orientation is one of the important topics of study in the field of non-linear control. The type of pendulum that has been used, which is the focal point of the proposed research work is a motorized propeller attached to the free end of a negligible mass rod, whose fixed end is pivoted about a rotatory shaft encoder, that calculates the angular position of the rod with respect to the vertical downward axis. As the mass of the rod is negligible as compared to the motorized propeller assembly, so the distance of the system's center of mass is the length of the rod. Control of the angular position of the driven pendulum is achieved manipulating the thrust force generated by the propeller using PID and ANN controller, which helps in lifting the pendulum against the gravitational force. General usage of a pendulum varies from the regulation of pendulum clocks, accelerometers, seismometers and scientific instruments to their wide use for studies in robotics, aerospace technology [9], marine navigation, self-balancing robot, and air thrust measurement etc.

II. MATHEMATICAL MODELLING OF AERO-PENDULUM

The schematic diagram of aero-pendulum and the free body diagram (F.B.D) of the same is shown in Fig. 1.

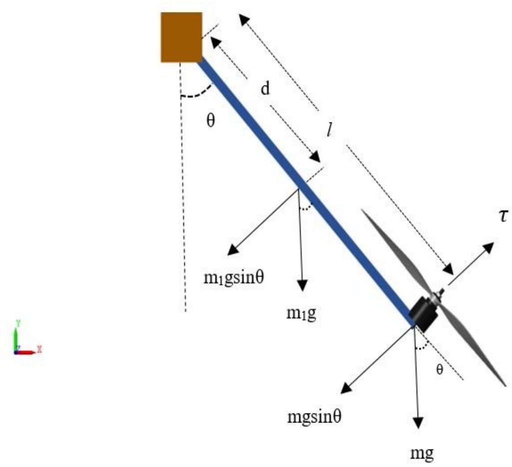


Fig. 1: Schematic diagram of an aero-pendulum

By using the equation of motion, the mathematical model for an angular position θ can be represented by the below-given equations:

$$\tau = I\ddot{\theta} + C\dot{\theta} + m_1 gd sin\theta + mgl sin\theta \quad (1)$$

$$\tau = l \times F \quad (2)$$

$$F = K_m V \quad (3)$$

$$lK_m V = I\ddot{\theta} + C\dot{\theta} + m_1 gd sin\theta + mgl sin\theta \quad (4)$$

Where: I is the moment of inertia (kgm^2) of propeller assembly, C is the viscous damping coefficient (Nms/rad), m_1 is the mass of pendulum rod (Kg), m is the mass of propeller assembly (Kg), g acceleration due to gravity (m/s^2), l length of pendulum rod (cm), d is the distance from the centre of rod to the pivot point (cm), θ is the angular position of pendulum rod (degree), τ is the torque produced by thrust force (Nm), F is the thrust force (N), V is the source voltage (v).
Finally, when the pendulum settles to equilibrium position or steady-state condition.

i.e. $\ddot{\theta}_{ss} = \dot{\theta}_{ss} = 0$, and equation (4) reduced to:

$$K_m V = mgsin\theta_{ss} \quad (5)$$

Or

$$K_m = \frac{mgsin\theta_{ss}}{V} \quad (6)$$

The following approximations were taken to obtain a linearized model:

- As work carried out by H. Kizmaz [1] to linearize the model before implementing a controller, the pendulum rod is considered much lighter than propeller assembly i.e. $m_1 \approx 0$.
- Moreover, in their work it has been experimentally established that relation between the supply DC voltage and angular position of pendulum rod is approximately linear between 0^o to 60^o i.e. $sin\theta \approx \theta$ is taken to derive the linear model of aero-pendulum.

After taking Laplace transform of equation (4), and considering the above assumptions, linearized model transfer function of aero-pendulum can be represented by equation (7).

$$\frac{\theta(s)}{V(s)} = \frac{K_m l/I}{s^2+\frac{C}{I}s+\frac{mgl}{I}} \quad (7)$$

It can be observed from the governing dynamic equation (1) of aero-pendulum that like most of the practical systems, it has non-linear dynamics. Most studies in the literature[1], [2], [4]–[7] uses the linearized model of aero-pendulum for simulation. On the contrary, the proposed work carried in this study to control the angular position of aero-pendulum by developing a 3D model using Simsacpe/Multibody technique in MATLAB environment, in which aero-pendulum model incorporates nonlinearities. Also in almost all the previous works, analysis is being carried for single angular position, but the work carried out in this paper consider operation on different angular positions.

III. Methodology

The presented study simulates a 3-D multibody model of aero-pendulum as shown in Fig. 2 using MATLAB simscape. Physical specifications of the aero-pendulum are mentioned in table 1 and are intended to be implemented in real-time in future work.

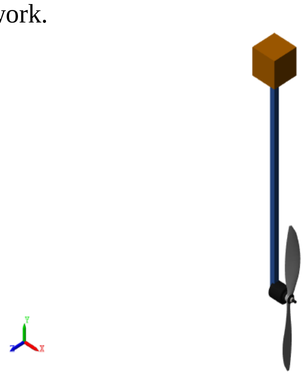


Fig. 2: 3D model of aero-pendulum

Table 1. Parameters of Aero-pendulum.

Parameter	**Specification**
Mass of motor and propeller assembly	0.0875 kg
Length of the pendulum rod	40cm
Viscous friction coefficient	0.04Nm/rad
Gravitational acceleration	9.81m/s^2

To control the angle (θ) of the aero-pendulum, which is the angle of the pendulum rod with negative Y axis, the speed of the propeller attached to it needs to be controlled, which exerts the required thrust force, to meet the requisite angle. After measuring the angular position of the pendulum with the help of an angular position sensor, it has been compared with the desired or reference angular position and the error is fed to the controller which produces the actuation input, fed to propeller assembly to meet the requirement.

In this work, first, a PID controller is incorporated to control the aero-pendulum angular position to get the desired angle with optimum performance. The parameters of the PID controller were first auto-tuned in MATLAB. Further to refine the response, manual tuning was done. Satisfactory responses were obtained for the values of K_P, K_I and K_D mentioned in table 2.

Table 2. Gain values of PID controller

Parameter	**Value**
K_P	1.35
K_I	0.85
K_D	0.06

After simulating, obtained response of aero-pendulum angular position for various input or desired angular position, the input-output data of PID controller is used to train an ANN using Levenberg-Marquardt algorithm. The Levenberg-Marquardt algorithm is a blend of Gradient Descent and the Gauss-Newton method. Finally, the PID controller is replaced with a trained ANN controller and responses for various inputs angular positions are obtained and compared for various time response specifications.

- ***ANN modelling***

An ANN with 15 neurons in the hidden layers is designed in offline mode using samples of input and output data from PID controller, out of which 70% samples are used for training, 15% for each validation and testing. Levenberg-Marquardt algorithm is used to train the ANN controller with 1000 iterations. It is observed that the error i.e. target-output has an average value of 1.179 degrees for most of the instances in all three training, validation and testing data sets. This shows that the network is trained, validated and tested with good accuracy. After successfully training the ANN controller, the same inputs which were used earlier while using PID controller are utilized in simulation with ANN controller and the response of the same is shown in Fig. 4. The Simscape model is again simulated while using ANN controller in place of the PID controller.

IV. RESULTS AND DISCUSSION

The Simscape model of closed-loop aero-pendulum using PID controller is simulated for stair-case input of different angles at different time instants with a simulation period of 120sec. The responses are shown in Fig.3. These responses from various reference inputs are further utilized to train an ANN controller. Fig. 3 shows the input-output response of aero-pendulum angular position when the PID controller is used. In the figure, the black line shows the desired or reference angular position and the red line shows the actual angular position of the aero-pendulum in degree. From the response, it can be seen that for smaller reference angle, PID controller provide good reference tracking with fair transient response, but for larger value of reference angles, the performance starts deteriorating with the response having higher peak overshoot and becomes more and more sluggish as the reference input is increased. It is observed that the response becomes unstable as the value of the input angle goes beyond 80 degrees while using PID controller.

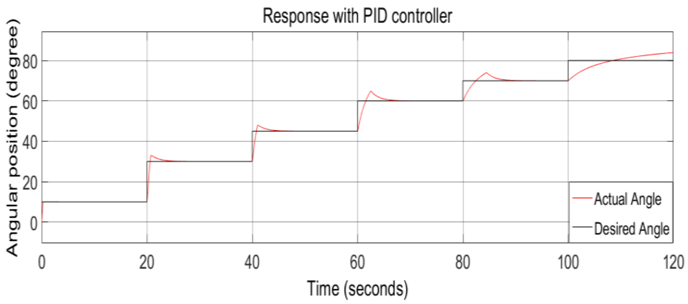


Fig. 3: Response using PID controller

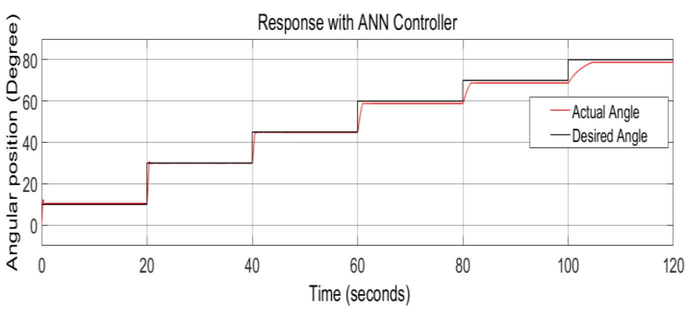


Fig. 4: Response using ANN controller.

Responses from both the controllers are compared and it is observed that although for small reference angles, the ANN controller produced high overshoot in the response. While for higher angles, it provided a much better response as compared to when the PID controller is used. For input angles greater than 80^o, the aero-pendulum which became unstable when the PID controller was used, gave a stable response for all valid input angles up to 90^o while using the ANN controller.

The root mean square error calculated between the input angles and output angles was less in the case of ANN controller. Table 3 depicting the same is shown below.

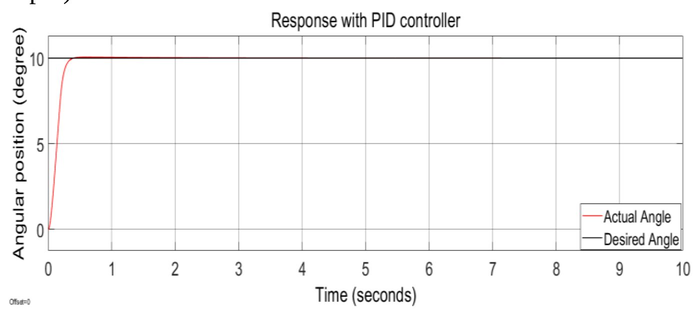
Table 3. Root mean square error for staircase input

Controller	Root mean square error
PID	2.34
ANN	2.04

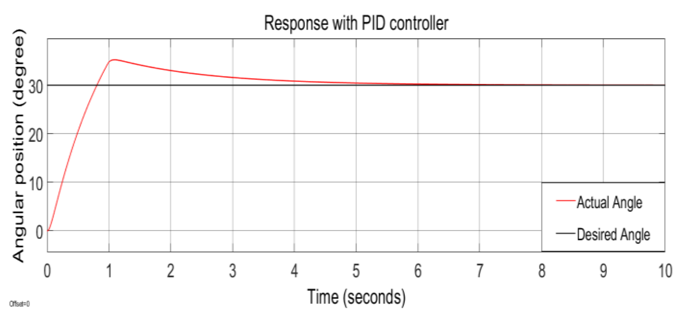
To have a detailed analysis of response while using either controller, different step input/reference angles are given and the response i.e., actual angle of the aero-pendulum is analysed by finding rise time (t_r), percentage overshoot (M_p), steady-state error (*sse*) and root mean square error (RMSE) between reference input angle and output actual angle in degrees.

1. *Aero-pendulum angle control using PID controller*

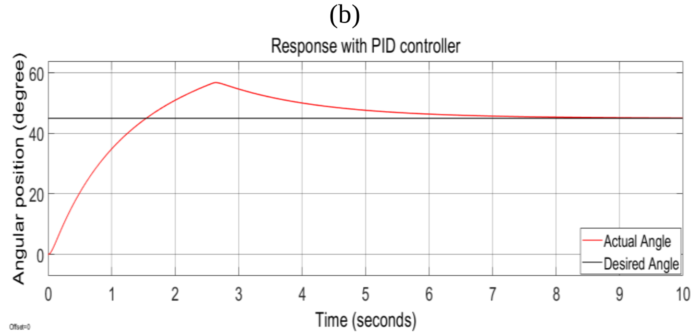
In the following figures, the desired angle/reference angle (black colour) is a step input of different magnitudes and the actual angle of the aero-pendulum (red colour) with the vertical downward axis are shown below. The responses are obtained for different values of desired/input angular positions 'Θ' (step input).



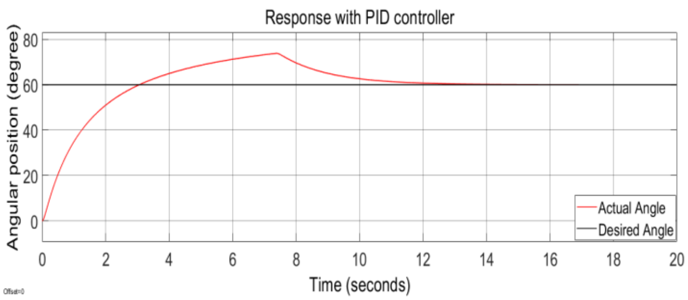
(a)



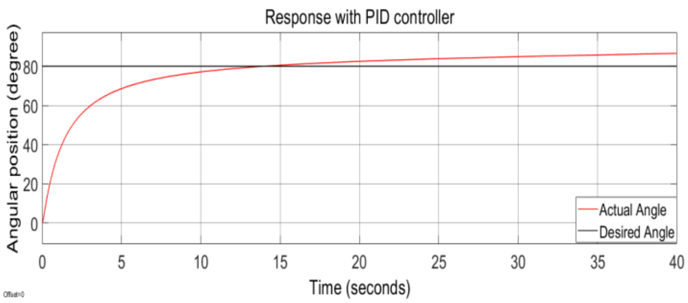
(b)



(c)



(d)



(e)

Fig.5: (a) ϴ=10º, (b) ϴ=30º, (c) ϴ=45º, (d) ϴ=60º, (e) ϴ=80º

Table 4 depicts performance specification for step input of different magnitude by calculating Rise time (t_r), Peak over shoot (M_p), Steady state error (*sse*) and root mean square error (RMSE), while using PID controller.

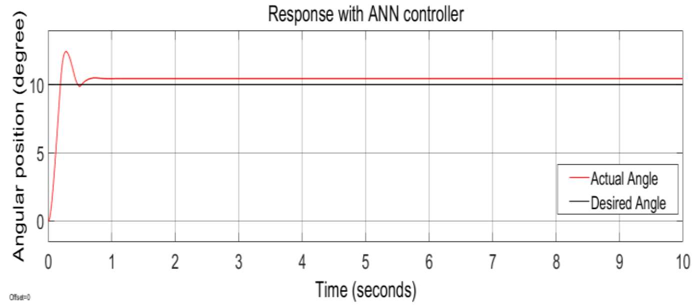
Table 4. Performance specifications while using PID controller

Desired angle(º)	**t_r(s)**	**M_p(%)**	***sse*(º)**	**RMSE(º)**
10º	0.1875	0.5051	1.3596×10^{-4}	1.0289
30º	0.6025	17.0588	0.0172	5.0531
45º	1.1503	25.9494	0.1034	9.8771
60º	2.1507	22.8395	2.6620	11.4655

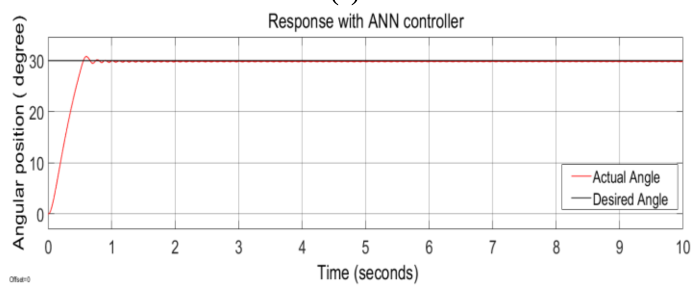
When the input angle is 80º, the response becomes very sluggish and unstable which can be seen in Fig. 5 (e). The angle of the pendulum kept on increasing, even after about 15sec when the aero-pendulum angle reached 80º for the first time, but the aero-pendulum angle did not settle down.

2. ***Aero-pendulum angle control using ANN controller***

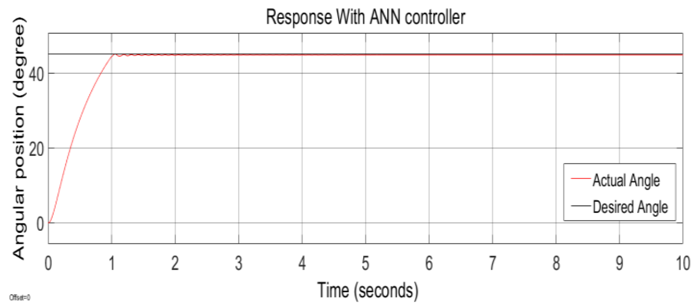
Same step inputs are used again in simulation while using ANN controller in place of PID controller. In the following figures, the desired angle/reference angle (black colour) is a step input of different magnitudes and the actual angles of the aero-pendulum with the vertical downward axis (red colour) are shown below.



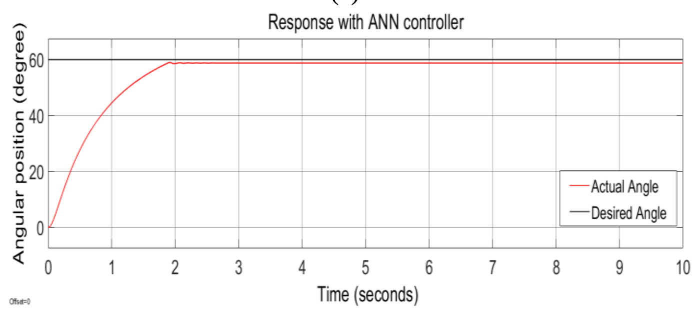
(a)



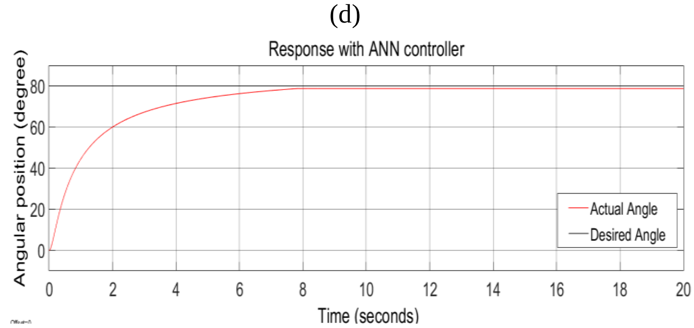
(b)



(c)



(d)



(e)

Fig. 6: (a) ϴ=10º, (b) ϴ=30º, (c) ϴ=45º, (d) ϴ=60º, (e) ϴ=80º

- Performance analysis of aero-pendulum, while using ANN controller.

Table 5. Performance specifications while using ANN controller.

Desired angle(°)	t_r(s)	M_p(%)	sse(°)	RMSE(°)
10°	0.1346	18	0.4356	1.0749
30°	0.3910	3.4658	0.1255	4.2008
45°	0.7310	0.7051	0.2121	7.6307
60°	1.2909	0.5051	1.2143	12.1551
80°	3.5738	0.3021	1.2794	15.9048

From table 4 and 5, it can be observed that for smaller reference angles such as 10°, although PID controller performed better in terms of overshoot (M_p), steady-state error (sse) and root mean square error (RMSE) compared to ANN controller, but the later has less rise time for almost all the given input angles. Also as the reference input angle increased, the later one gave better performance and the system becomes unstable when the PID controller was used for angles greater than 80°, contrary to which ANN controller was able to control the angular position of aero-pendulum up to 90°, the response of the same is shown in Fig. 7.

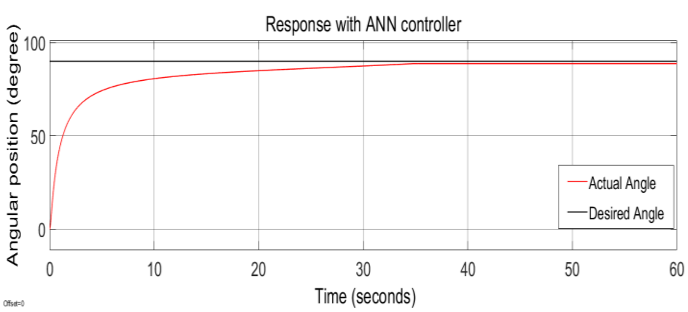


Fig. 7: Response for ϴ=90° using ANN controller.

V. Conclusion

A 3-D model of aero-pendulum has been developed using Simscape Multibody in MATLAB. Unlike developing a transfer function model in Simulink in which linearization has to be done, multibody modelling is 3-D modelling that includes non-linearities related to the physical system. First, a PID controller was used to control the angular position of the driven pendulum, then input-output data which consisted of ‘400000×1’ samples used in designing ANN controller. Levenberg-Marquardt algorithm was utilized for training purpose. Finally, the angular position control of aero-pendulum was successfully achieved by using the well trained ANN controller, which showed good performance and robustness over the PID controller for input angle varies from 0° to 80°.

VI. Future work

The results obtained from the present study encourages the implementation of trained ANN controller on a physical aero-pendulum system in real-time for various conditions, like breeze environment, how the system will behave if immersed in water, etc. Additionally, deep neural network controller and other training algorithms can also be implemented so that a comparison can be done to check the performance of other machine learning controllers and different algorithms for different mechatronic systems.

References

[1] H. Kizmaz, S. Aksoy, and A. Muhurcu, “Sliding mode control of suspended pendulum,” *Proc. - Int. Symp. Mod. Electr. Power Syst. MEPS’10*, 2010.

[2] M. M. Job and P. S. H. Jose, “Modeling and control of mechatronic aeropendulum,” *ICIIECS 2015 - 2015 IEEE Int. Conf. Innov. Information, Embed. Commun. Syst.*, pp. 3–7, 2015, doi: 10.1109/ICIIECS.2015.7192959.

[3] E. T. Enikov and G. Campa, “Mechatronic aeropendulum: Demonstration of linear and nonlinear feedback control principles with MATLAB/simulink real-time windows target,” *IEEE Trans. Educ.*, vol. 55, no. 4, pp. 538–545, 2012, doi: 10.1109/TE.2012.2195496.

[4] O. Saleem, M. Rizwan, A. A. Zeb, A. H. Ali, and M. A. Saleem, “Online adaptive PID tracking control of an aero-pendulum using PSO-scaled fuzzy gain adjustment mechanism,” *Soft Comput.*, vol. 24, no. 14, pp. 10629–10643, 2020, doi: 10.1007/s00500-019-04568-1.

[5] S. S. Raju, T. S. Darshan, and B. Nagendra, “Design of Quadratic Dynamic Matrix Control for Driven Pendulum System,” *Int. J. Electron. Commun. Eng.*, vol. 5, no. 3, pp. 363–370, 2012.

[6] A. Mohammadbagheri and M. Yaghoobi, “A new approach to control a driven pendulum with PID method,” *Proc. - 2011 UKSim 13th Int. Conf. Model. Simulation, UKSim 2011*, pp. 207–211, 2011, doi: 10.1109/UKSIM.2011.47.

[7] M. R. Rahimi Khoygani, R. Ghasemi, and D. Sanaei, “Design Controller for a Class of Nonlinear Pendulum Dynamical System,” *IAES Int. J. Artif. Intell.*, vol. 2, no. 4, 2013, doi: 10.11591/ij-ai.v2i4.4164.

[8] K. Cheon, J. Kim, M. Hamadache, and D. Lee, “On Replacing PID Controller with Deep Learning Controller for DC Motor System,” *J. Autom. Control Eng.*, vol. 3, no. 6, pp. 452–456, 2015, doi: 10.12720/joace.3.6.452-456.

[9] K. Cheon, J. Kim, M. Hamadache, and D. Lee, “On Replacing PID Controller with Deep Learning Controller for DC Motor System,” *J. Autom. Control Eng.*, vol. 3, no. 6, pp. 452–456, 2015, doi: 10.12720/joace.3.6.452-456

[10] J. Marholt and F. Gazdoš, “Modelling, identification and simulation of the inverted pendulum ps600,” *Acta Montan. Slovaca*, vol. 15, no. 1, pp. 14–18, 2010.

[11] B. G. P. B. Gowri Prasad, S. H. S. Hemachandra, B. S. B. Suneetha, and A. J. A. Jayanth, "Speed Generation and Control of DC Motor Using Neural Network Configuration," *Int. J. Sci. Res.*, vol. 2, no. 5, pp. 106–109, 2012, doi: 10.15373/22778179/may2013/39.

[12] S. B. Kumar, M. H. Ali, and A. Sinha, "Design and Simulation of Speed Control of DC Motor by Fuzzy Logic Technique with Matlab / Simulink," *Int. J. Sci. Res. Publ.*, vol. 4, no. 7, pp. 2–5, 2014.

[13] K. J. Åström and T. Hägglund, "The future of PID control," *Control Eng. Pract.*, vol. 9, no. 11, pp. 1163–1175, 2001, doi: 10.1016/S0967-0661(01)00062-4.

[14] J. Abraham and S. Shrivastava, "Dc Motor Speed Control Using Machine Learning Algorithm," *Int. J. Eng. Res. Technol.*, vol. 7, no. 04, pp. 456–470, 2018.